Ultraluminous X-ray sources - new distance indicators?

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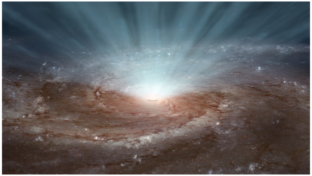
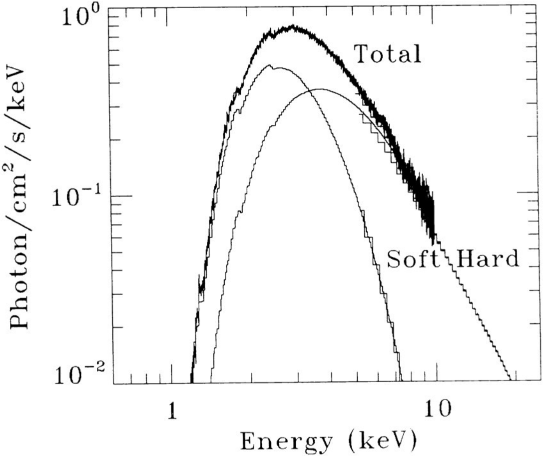
Karol Bresler, Bartosz Bełdycki, Jerzy Madej, Tek P. Adhikari



23.05.2018, Heraklion, Greece

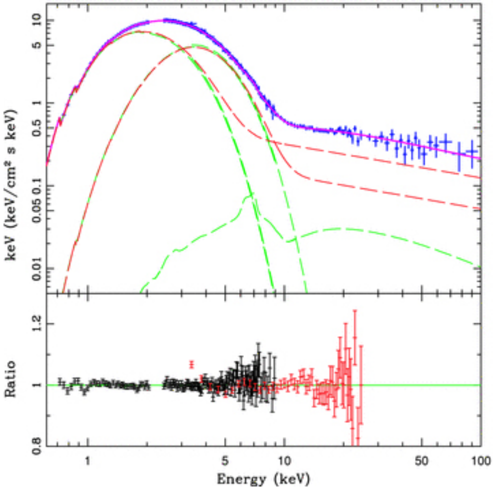
CAMK PAN
UNIWERSYTET WARSZAWSKI
STRONG GRAVITY
EU FP7-SPACE research project 312789 2013 - 2017

X-ray binaries: Zhang +00, GRS 19151+105

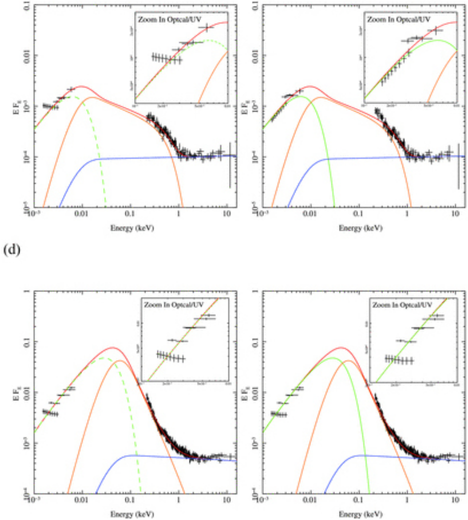


Observations of accreting sources

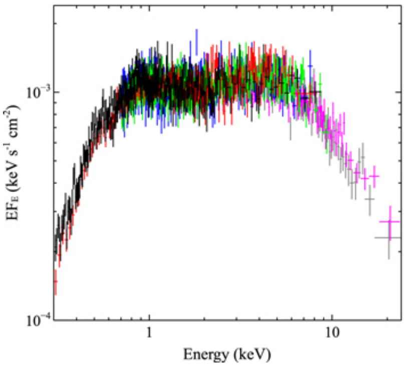
X-ray binaries: Kolehmainer +11, GX 339-4

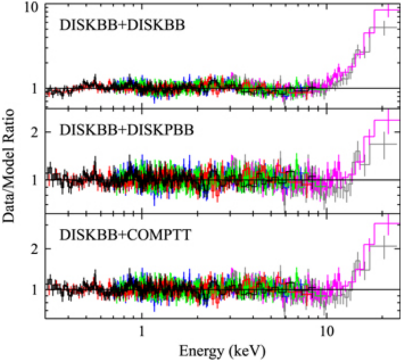


Seyfert galaxies: Jin +12, J112328+052823, PG 1415+451



ULX sources: Walton +15, Holmberg II X-1





Jerzy Madej

- Professor at the University of Warsaw

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4. CITA, University of Toronto, postdoc 1 year

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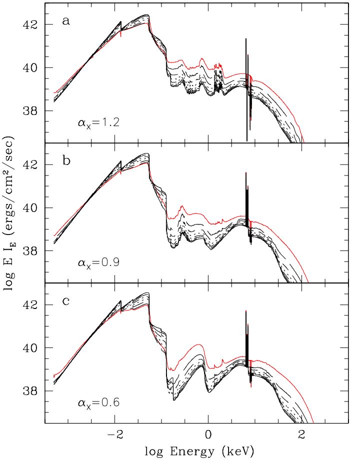
Emission coefficient j_ν is the sum of three terms, $j_\nu = j_\nu^{th} + j_\nu^{sc} + j_\nu^{fl}$.



Radiative transfer equation, Różańska +08

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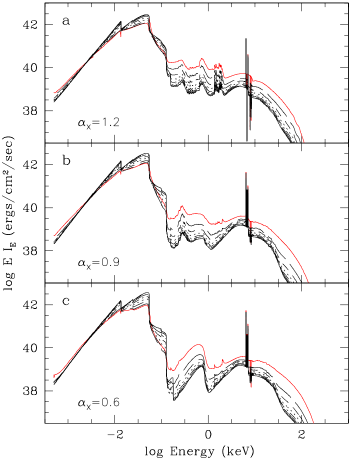
- Hydrostatic equil. => $\frac{dP}{dz}$



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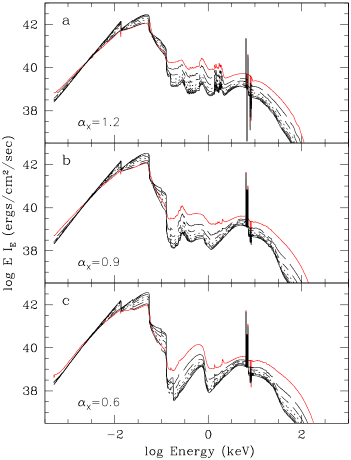

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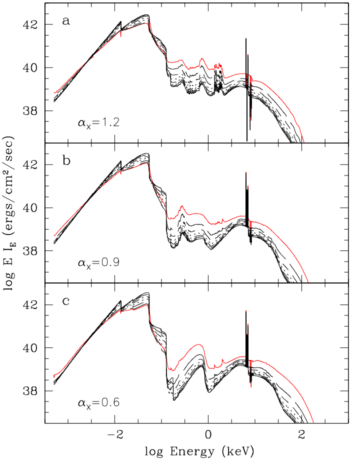
- Radiative equil. => $\frac{dT}{dz}$
- EoS - usually ideal gas



Model atmosphere calculations - glossary of terms

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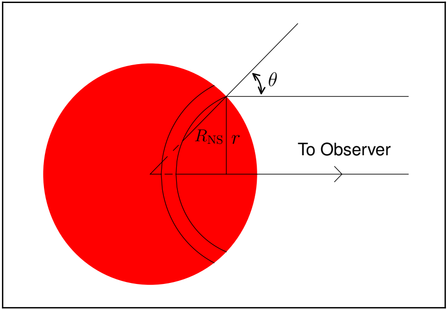
3. Infinitesimal energy $d\mathcal{F}_\nu$ can be measured by a distant observer in flat space, over infinitesimal part of full solid angle

$$d\mathcal{F}_\nu = I_\nu d\omega,$$

subtended by the area as seen by an observer. It is NOT an intrinsic property of the source in erg cm^{-2} s^{-1} Hz^{-1}.

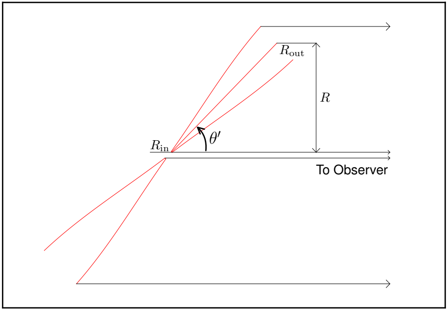
Spherically symmetric stars - ideal model of NS



$$\mathcal{F}_{\nu,\rm NS} = 2\pi\left(\frac{R_{\rm NS}}{D}\right)^2 \int_0^1 I_\nu \mu d\mu = \left(\frac{R_{\rm NS}}{D}\right)^2 F_\nu$$

The observed intensity per detector area is proportional to the flux emitted locally from 1 cm^2 of the star's surface, only due to the spherical shape of the emitting region. Mihalas 1976.

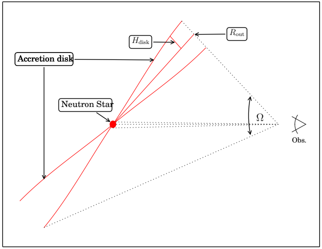
Axially symmetric accretion disk - Shakura & Sunyaev 1973

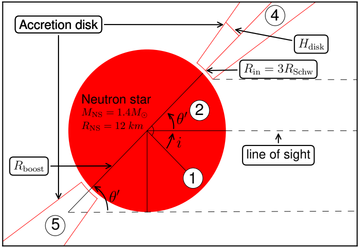


$$\mathcal{F}_{\nu,\rm AD} = \int_{\Omega} I_{\nu} d\omega = 2\pi \frac{\sin\theta'}{D^2} \int_{R_{\rm in}}^{R_{\rm out}} I_{\nu} R dR,$$

Monochromatic intensity, I_{ν} emitted in the specific direction is integrated over the disk surface from the inner to outer disk radii.

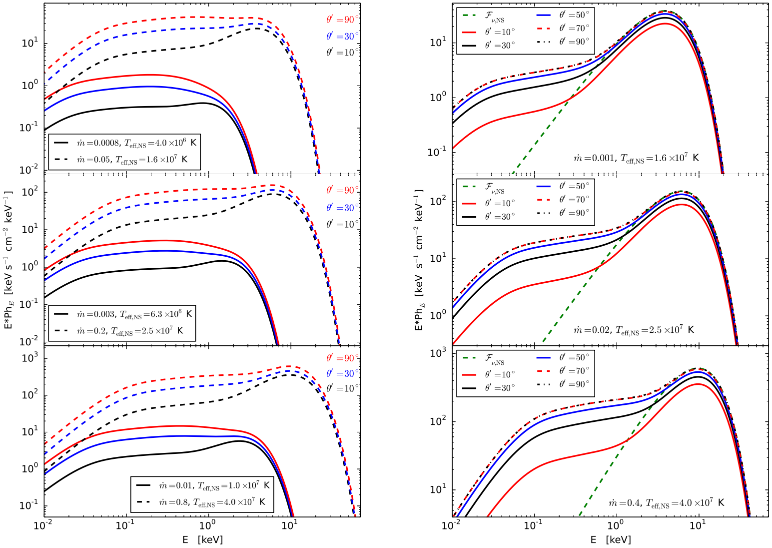
Neutron star with an accretion disk, Różańska +17



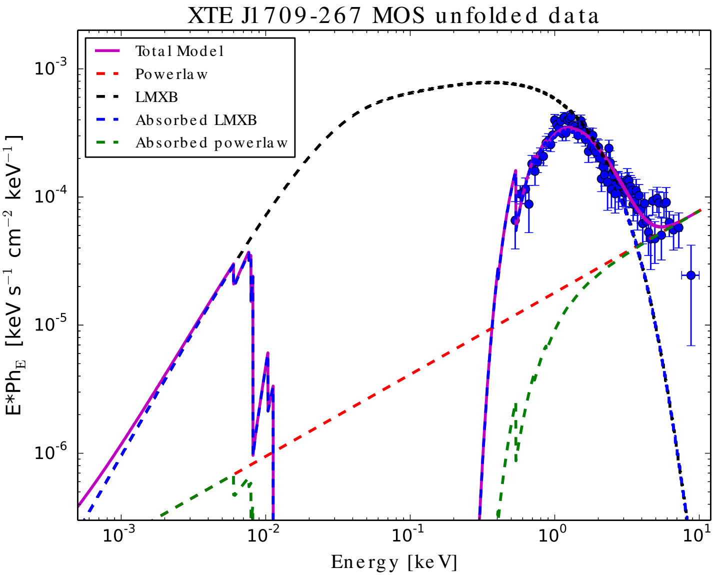


$$\begin{aligned}
\mathcal{F}_{\nu,\rm All} &= \left(\frac{1}{D}\right)^2 \Bigg[\pi R_{\rm NS}^2 \left(\int_0^1 I_\nu \mu d\mu + \int_{\cos\theta'}^1 I_\nu \mu d\mu\right) \\
&+ 2\left(\int_0^{R_{\rm NS}} I_\nu \sin\theta' \sqrt{R_{\rm NS}^2 - x^2}\, dx - \int_0^{R_{\rm NS}\sin\theta'} I_\nu \sqrt{R_{\rm NS}^2 \sin^2\theta' - x^2}\, dx\right) \\
&+ \pi \sin\theta' \left(\int_{R_{\rm in}}^{R_{\rm out}} I_\nu R dR + \int_{R_{\rm boost}}^{R_{\rm out}} I_\nu R dR\right)\Bigg]
\end{aligned}$$

LMXB at different viewing angles, Różańska +17



X-ray observations of XTE J1709-267 by *XMM-Newton*



NUSTAR/XMM-Newton data of ULXs, Różańska +18

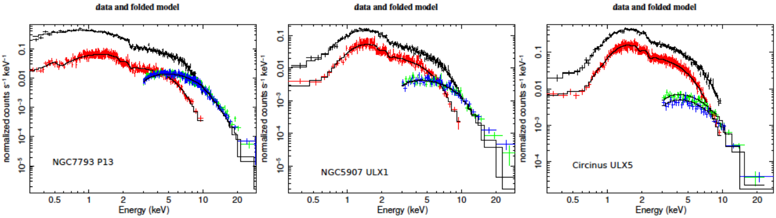


Fig. 1. Normalized counts from all detectors used in our spectral fitting analysis for P13, ULX1, and ULX5 respectively. Black and red crosses correspond to the *XMM-Newton* detectors EPIC-pn and EPIC-MOS. Green and blue crosses are data from *NuSTAR* FPMA and FPMB respectively. Black solid lines are the best fitted models.

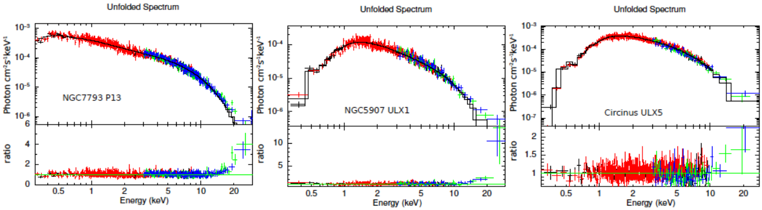


Fig. 2. Upper panels shows unfolded photon spectra from all detectors used in our spectral fitting analysis, while lower panels present the ratio i.e. data divided by model. All colors have the same meaning as in Fig. 1.

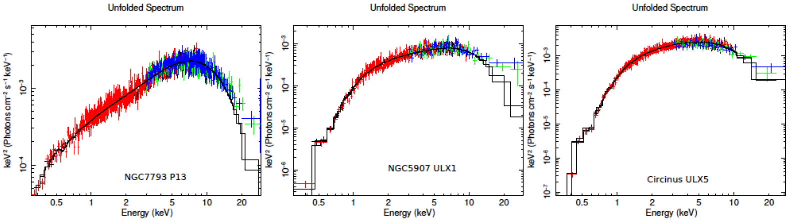


Fig. 3. Unfolded energy spectrum from all detectors used in our spectral fitting analysis. $E * F_{\rm E}$ quantity is plotted to show the maximum emission from hard energy tail which is associated with the emission. Black and red crosses correspond to the *XMM-Newton* detectors EPIC-pn and EPIC-MOS. Green and blue crosses are data from *NuSTAR* FPMA and FPMB respectively. Black solid lines are the best fitted models.

The single model consists of two emitting regions with mutual attenuation taken into account. The statistic is extremely good:

Src. Name	NGC7793 P13	NGC5907 ULX1	Circinus ULX5
χ^2	1.08	1.01	1.14

Fitting parameters with the *tbnew*nsmcbb* model.

Src.	Model	Parameter	Value	Unit
P13	*tbnew*	$N_{\rm H}$	$4.77^{+0.45}_{-0.44} \times 10^{20}$	cm^{-2}
	nsmcbb	$T_{\rm eff,NS}$	$1.819 \pm 0.025 \ \times 10^{7}$	K
	nsmcbb	$T_{\rm in}$	$1.215^{+0.036}_{-0.046} \times 10^{7}$	K
	nsmcbb	θ'	10 ± 6.59	deg
	nsmcbb	N	$8.62 \pm 0.54 \times 10^{-6}$	–
ULX1	*tbnew*	$N_{\rm H}$	$4.45^{+0.13}_{-0.2} \times 10^{21}$	cm^{-2}
	nsmcbb	$T_{\rm eff,NS}$	$1.776^{+0.071}_{-0.032} \times 10^{7}$	K
	nsmcbb	$T_{\rm in}$	$9.014^{+2.809}_{-0.244} \times 10^{6}$	K
	nsmcbb	θ'	70 ± 1.87	deg
	nsmcbb	N	$2.33^{+0.70}_{-0.42} \times 10^{-6}$	–
ULX5	*tbnew*	$N_{\rm H}$	$5.97^{+0.01}_{-0.01} \times 10^{21}$	cm^{-2}
	nsmcbb	$T_{\rm eff,NS}$	$1.633^{+0.117}_{-0.109} \times 10^{7}$	K
	nsmcbb	$T_{\rm in}$	$1.261^{+0.398}_{-0.075} \times 10^{7}$	K
	nsmcbb	θ'	$12.49^{+1.74}_{-0.71}$	deg
	nsmcbb	N	$15.23 \pm 0.94 \times 10^{-6}$	–

Distance from the model normalization, Różańska +18

Src.	Parameter	Value	Unit
P13	χ^2/dof	1344/1245	–
	$F_{\rm X}$(2-10 keV)	$4.36\ \times 10^{-12}$	erg s^{-1} cm^{-2}
	$F_{\rm X}$(0.3-30 keV)	$6.83\ \times 10^{-12}$	erg s^{-1} cm^{-2}
	$D = 10/\sqrt{N}$	$\mathbf{3.41}^{+0.11}_{-0.10}$	Mpc
	$L_{\rm X}$(0.3-30 keV)	$9.59\ \times 10^{39}$	erg s^{-1}
ULX1	χ^2/dof	867/859	–
	$F_{\rm X}$(2-10 keV)	1.73×10^{-12}	erg s^{-1} cm^{-2}
	$F_{\rm X}$(0.3-30 keV)	2.81×10^{-12}	erg s^{-1} cm^{-2}
	$D = 10/\sqrt{N}$	$\mathbf{6.55}^{+0.69}_{-0.81}$	Mpc
	$L_{\rm X}$(0.3-30 keV)	1.49×10^{40}	erg s^{-1}
ULX5	χ^2/dof	872/762	–
	$F_{\rm X}$(2-10 keV)	5.78×10^{-12}	erg s^{-1} cm^{-2}
	$F_{\rm X}$(0.3-30 keV)	9.18×10^{-12}	erg s^{-1} cm^{-2}
	$D = 10/\sqrt{N}$	$\mathbf{2.60}^{+0.05}_{-0.03}$	Mpc
	$L_{\rm X}$(0.3-30 keV)	7.49×10^{39}	erg s^{-1}

Distance from the model normalization, Różańska +18

In case of two ULXs the distant determination from our method agrees with previous measurements:

Src. Name	NGC7793 P13	NGC5907 ULX1	Circinus ULX5
D [Mpc]	$\mathbf{3.41^{+0.11}_{-0.10}}$	$6.55^{+0.69}_{-0.81}$	$\mathbf{2.60^{+0.05}_{-0.03}}$
Previous	3.9 C.	13 T.	4 T.
distances	**3.4** C.	17 T.	**2.79** RV.
Method	Cepheid	Tully	Radial Vel.
Ref.	Pietrzyński +10	Tully +16	Koribalski +04

Summary

1. ULXs may contain hot neutron star in the center. Proper integration over emitting region containing two systems NS and AD, provides excellent fit.
2. The successful fit with single model component allows for distant determination.
3. The model should be used in case of X-ray binaries and AGN with proper definition of second emitting region as hot corona. Of course assuming that the first one is an AD.
4. Our model does not include ray tracing and radiative transfer calculation. We aimed to show purely geometrical effect.
5. The more general result is that any double bump observed in X-ray domain may be an evidence of two emitting regions and non-spherical source geometry.

THANK YOU